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A Sweep-Frequency Radiometer for Terrestrial and Planetary Atmospheres

Alan H. Barrett

[redacted]

NASA CR 52599

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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A Sweep-Frequency Radiometer For Terrestrial and Planetary Atmospheres

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ABSTRACT

The feasibility and desirability of using microwave spectral lines of molecules to study the properties of planetary atmospheres will increase as the payload and power capabilities for deep-space exploration increase. This Memorandum presents some of the scientific justifications for developing special microwave equipment and the requirements and/or specifications of this equipment. The fundamental approaches to receiver development which must be explored are also discussed.

I. INTRODUCTION[1]

As the payload and power capabilities of satellite and deep-space probes are increased, it will become increasingly more desirable and feasible to utilize the microwave spectral lines of molecules as a means of studying the properties of a planetary atmosphere. For reasons discussed herein, detailed microwave studies of a planetary atmosphere will have to be performed from space vehicles which are either orbiting or passing near the target planet. Coupled with this requirement is the fact that the microwave radiometer which would be desirable for use has yet to be developed; thus, the need for long-range planning is obvious.

It is perhaps surprising that plans are being formulated to study planetary atmospheres by microwave techniques when such techniques have not been utilized to study the terrestrial atmosphere. The reasons for this are twofold: first, the terrestrial atmosphere is readily available for study by more direct means. Indeed, the gross properties of our atmosphere were known before microwave techniques were developed as a research tool. Second, the microwave spectrum of interest for studying the terrestrial atmosphere can be roughly defined as between 1.5 cm and 1 mm, and, until very recently, reliable equipment was not readily available for use in much of this wavelength region.

This memorandum is intended to give some of the scientific justifications for developing the special microwave equipment required and the requirements and/or specifications that the equipment would have to meet, depending on the experiment to be done, and also to discuss some of the fundamental approaches to receiver development that will have to be explored.

[1]The author is a member of the staff of the Research Laboratory of Electronics, Massachusetts Institute of Technology, and an Associate Professor in the Department of Electrical Engineering. This work was started while the author was a member of the Astronomy Department of the University of Michigan.

II. TERRESTRIAL AND PLANETARY MICROWAVE EXPERIMENTS

In considering the exploration of the terrestrial and planetary atmospheres, two basic and obvious questions arise:

1. What molecules are known to exist, or are expected to exist, in the atmospheres of planets?
2. What are the microwave properties, if any, of these molecules?

The answer to the first question is supplied, of course, by the observations made to date. Table 1 gives the molecular constituents, in order of decreasing abundance, that have been detected in some of the planets. The molecules listed in parentheses have not been detected but might be expected to be present on the basis of what is known about the atmosphere and the chemistry of the molecules. The present discussion will be limited to the planets listed in Table 1. Mercury is not believed to have an atmosphere, and Saturn, Uranus, and Neptune closely resemble Jupiter with regard to atmospheric constituents. Table 1 clearly illustrates the contrast between the number of identified molecules in the Earth's atmosphere and the same number in our neighboring planets. It is to be expected that most of the suspected molecules actually do exist in the atmospheres of the other planets but that their abundance is sufficiently small that they have escaped detection by conventional spectroscopy.

Table 1. Molecular constituents of the planets

Planet	Molecules
Venus	CO_2, H_2O (N_2, N_2O, NO_2, NO, CO, CH_4, NH_3 A, C_3O_2, O_2, O_3)
Earth	N_2, O_2, H_2O, A, CO_2, Ne, He, CH_4, Kr, N_2O, H_2, O_3, CO, SO_2, OH,NH_3 (NO)
Mars	CO_2 (N_2, A, O_2, O_3, H_2O, CO, N_2O, NO_2, NO, NH_3, CH_4)
Jupiter	H_2, CH_4, NH_3 (He, Ne, A, H_2O)
Note: ( ) indicates molecule not detected but expected to be present.	

The second question – What are the microwave properties, if any, of these molecules? – brings the unfortunate answer that many of the abundant molecules in the planetary atmospheres do not have any microwave spectra. This is a consequence of the fact that, if the center of mass of a molecule and the center of the electronic-charge distribution coincide, the molecule will not have a dipole moment and will not interact with microwave radiation. These conditions are met in practically all symmetric molecules, of which the homonuclear molecules are an obvious example. Thus, H_2, N_2, CO_2, and CH_4 are unobservable by microwave techniques. The molecule O_2 is a familiar exception to the preceding statements because of the arrangement of its electron spins. The interaction of microwaves with O_2 is inherently rather weak, but it is important in the Earth's atmosphere because of its large abundance and the presence of many overlapping transitions. In addition to these molecules, the inert gas atoms, He, Ne, A, and Kr, have no microwave transitions in their ground states and may be dropped from further consideration. Thus, Table 2 lists the molecules that are known, or might be expected, to exist in planetary atmospheres and which have microwave transitions among their low-lying energy levels. It will be noted that H_2O and NH_3 are common to all planets listed.

Table 2. Molecular constituents with microwave transitions in low-energy levels

Planet	Molecules
Venus	H_2O (N_2O, NO_2, NO, CO, NH_3, OH, C_3O_2, O_2, O_3)
Earth	O_2, H_2O, N_2O, O_3, CO, SO_2, OH,NH_3 (NO)
Mars	(O_2, O_3, H_2O, CO, N_2O, NO_2, NO, OH, NH_3)
Jupiter	NH_3 (H_2O)
Note: ( ) indicates molecule not detected but expected to be present.	

It is a fortunate circumstance that all the molecules listed in Table 2, with the exception of C_3O_2, have been studied in the microwave spectrum; hence, something is known about their resonant frequencies, line widths, intensities, and molecular structure. Outstanding, in this regard, is the NH_3 molecule, whose spectra has been more extensively studied than any other molecule. A list of the known NH_3 frequencies and their intensities is given in App. A. The frequencies of important transitions of the other molecules are listed in App. B.

It can readily be seen from the preceding discussion that one of the immediate scientific justifications for developing a sweep-frequency radiometer is the possible identification of molecules in the atmospheres of the planets. It can also be seen from the frequencies given in App. A and B that most of the lines lie in that portion of the spectrum where the terrestrial atmosphere is largely opaque, or nearly so. It is for this reason that experiments of this nature must be conducted from spacecraft.

Aside from the characteristics inherent in a molecule because of its structure, the shapes, widths, and intensities of microwave spectral lines in planetary atmospheres will depend on the temperature and pressure at the surface of the planet, the composition of the atmosphere, and on the variation of the temperature and pressure with altitude from the surface. This is particularly true for a spectral line which is sufficiently opaque that the radiation in the center of the line originates in the upper atmosphere of the planet (assuming the radiometer is orbiting the planet and not on the surface of the planet) while the radiation outside the line originates from the surface. Thus, by scanning in frequency, the radiation will originate at different levels in the atmosphere and will, of course, be representative of conditions at that level. Therefore, detailed studies of the line shapes and intensities will be invaluable in determining the properties of the atmosphere at all levels.

A third area of study which would be opened up by use of a sweep-frequency microwave radiometer is the time variation of the abundance of various molecules in the atmosphere. These variations would, of course, make themselves known by the changes in their spectral lines. Such changes could be the result of, for example, (1) local condensations or concentrations, such as clouds, within the antenna beam; (2) surface phenomena effecting the atmosphere above; (3) a true day-night variation as the spacecraft orbits the planet; (4) solar-induced variations. In this regard, attention should be called to the fact that the radio radiation from Jupiter has been found to be time-varying and the CO_2 emission from Venus has exhibited similar behavior.

Finally, a fourth scientific justification for the development of a sweep-frequency microwave radiometer can be mentioned. Such a radiometer could be used to study absorption lines in the terrestrial atmosphere where a detailed study has yet to be performed. This experiment would yield information on conditions in the upper atmosphere where the pressure is reduced such that the line widths become quite small. An example of the effect of pressure on line widths can be seen from Fig. 1 and 2

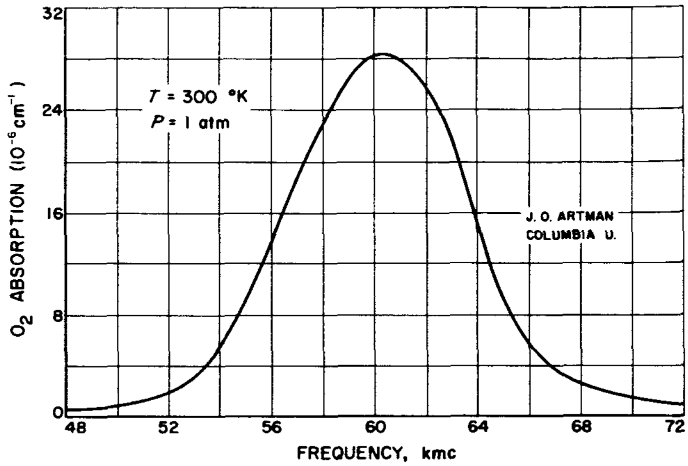

Fig. 1. Resultant absorption of pressure-broadened O_2 lines at 5 mm, P = 1 atm

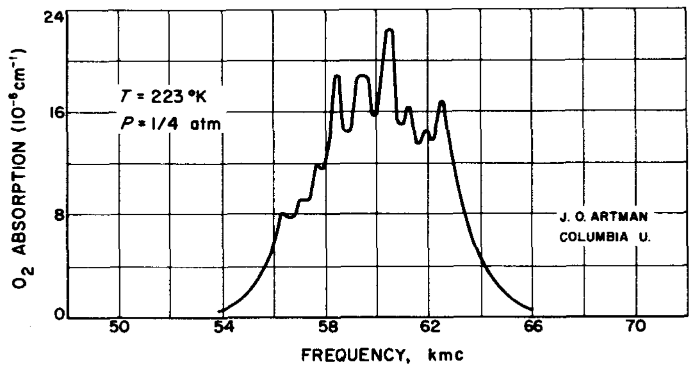

Fig. 2. Resultant absorption of pressure-broadened O_2 lines at 5 mm, P = ¼ atm

where the O_2 complex of lines is shown at pressures of 1 and ¼ atm.[2] Such studies would have two additional advantages: (1) they would serve as an excellent means of checking on the performance of a radiometer to be flown in a space probe, and (2) the interpretation of the results from the terrestrial atmosphere would be an invaluable aid in interpreting the results obtained from other planetary atmospheres.

[2] These figures are from the doctoral thesis of J. O. ARTMAN, Columbia U.

III. REQUIREMENTS OF A SWEEP-FREQUENCY RADIOMETER

1. The first requirement of any instrumentation of a scientific experiment in a spacecraft must be reliability. A sweep-frequency microwave radiometer will represent the state of the art at the time of its development and, as such, may be lacking in reliability, but it is imperative that the packaged model for space flight sacrifice performance in order to achieve reliability.

2. Power and weight requirements depend on many factors which are changing as advances in technology are made; therefore, a discussion of these factors will not be included here.

3. The frequency range of the radiometer will be governed by the experiments to be done. It can be seen from Table 2 and the Appendices that the frequency range from 20 kmc to 28 kmc encompasses the strong lines of NH_3, the H_2O line at 22.2 kmc, a line of N_2O, and lines of NO_2, OH, O_3, and SO_2. Thus this range, or a portion thereof, seems well suited for an effort to develop such a radiometer. A sweep-frequency range of 8 kmc centered at 24 kmc represents a ratio of only 1/3 of the center frequency and is feasible only if the sensitivity requirement is consistent with this range.

Two other possibilities suggest themselves from App. B. These are the O_2 lines which would require frequency limits of 50-70 kmc, or some fraction thereof, and the lines of O_2, N_2O, NO, O_3, and CO, which fall between the limits of 100 to 150 kmc. However, it is well known that millimeter receivers are more difficult to build and these receivers should probably follow the development of a *K*-band radiometer.

4. Specific details of bandwidth, integration time, sweep rate, sweep range, and temperature sensitivity will depend on the details of the experiment to be done. In fact, in any experiment these quantities are not independent. For example, the bandwidth and the sweep rate place an upper limit on the integration time and, of course, all quantities are important in determining the temperature sensitivity. If it is desired to study the H_2O line at 1.35 cm in the terrestrial atmosphere, it will be necessary to study a frequency width of about 6 kmc to include most of the line. However, it is entirely possible that much valuable information will be obtained from detailed studies of a more limited portion, perhaps 1 kmc or less. If a 6 kmc range is scanned in 10 min (10 mc/sec/sec) with a radiometer having a 20 mc bandwidth and a time constant of 1 sec, a rms noise temperature of 1°K would result if a receiver temperature of about 4500°K over the entire range could be maintained. The expected emission from terrestrial atmospheric H_2O is about 30°K for a system directed toward the zenith. If, on the other hand, the Sun is used as a background source, the H_2O line would appear in absorption and have a depth of about 1000°K, assuming the Sun fills the antenna beam. In this latter case, however, the receiver fluctuations can be expected to be a factor of 3 higher because of the 10,000°K antenna temperature. In any case, the large absorption signal expected from the Sun indicates that the preliminary data could be taken with a fairly crude system.

5. Adequate provision for calibration of the radiometer at all frequencies must be included in a final design. It is not unlikely that the gain and radio-frequency impedance will change throughout the wide range of frequencies to which the system is responsive; therefore, a calibration system must be incorporated to permit compensation to be made for these effects in the final data.

Because of lack of available data, it is considerably more difficult to evaluate the system which would be desirable for Venus or Jupiter experiments. In any event, the radiometer described above, which is presented only as a typical example, would be useful for studying H_2O in the atmosphere of Venus or NH_3 in the atmosphere of Jupiter.

Certainly the considerations developed in this and the following Section indicate that a detailed study of the H_2O line in the Earth's atmosphere is possible with present techniques. Furthermore, this would serve as an excellent "testing ground" for further developments.

IV. TYPES OF SPECTRAL-LINE RADIOMETERS

In the discussion thus far, it has tacitly been assumed that the microwave experiments would be performed with a sweep-frequency radiometer. However, it should be remembered that the scientific experiments call for an examination, in detail, of a selected portion of the spectrum and that this requirement does not, in itself, require a sweep-frequency system. Another means of accomplishing the same end would be with the use of a multi-channel receiver. Before any development work is undertaken, the following approaches should be given careful consideration:

1. A sweep-frequency superheterodyne radiometer. This receiver has been discussed in Sec. III and appears to be feasible with current techniques. A major problem in the development may be a crystal mixer which will perform over a wide frequency range. Also, in probe experiments, it should be borne in mind that, if the antenna is scanning a planet at the same time as the receiver is frequency scanning, the resultant data becomes impossible to unravel, for no means is available to correlate the receiver output changes as due to antenna position or frequency effects. In addition, the problem of image rejection or the effects of the lack of image rejection must be carefully considered.

2. A sweep-frequency "zero" intermediate-frequency (IF) radiometer. This receiver is similar to a superheterodyne radiometer except that the intermediate frequency is approximately zero. Such a system is currently in use at the University of Michigan as a solar receiver sweeping from 2000 to 4000 mc in 0.1 sec with a bandwidth of 5 mc. This type of receiver suffers from the same problems as a conventional superheterodyne, except for the problem of image rejection.

3. A wide-band receiver, using traveling-wave tubes, with a tunable microwave cavity preceding the amplification to limit the bandwidth. This receiver would have a high noise figure and/or unreliable *K*-band traveling wave tubes. In addition, gain variations throughout the band could be considerably in excess of 3 db. The receiver would not require a local oscillator.

4. A wide-band video receiver with a preselector, such as a tunable microwave cavity, to limit the bandwidth and afford a means of frequency scanning. This receiver may be noisy, but it would offer the considerable advantage of simplicity.

5. A multi-channel receiver. By means of several receivers tuned to various portions of the desired spectrum, considerable improvement in sensitivity is achieved. This system also has the very distinct advantage of giving data throughout the entire spectrum 100% of the time; whereas, a sweep-frequency receiver can give data only on that portion of the spectrum to which it is tuned at the time. Thus, a multi-channel receiver is ideally suited to a scanning antenna. The disadvantages include complexity and the intricate antenna-feed problem to ensure that the beam of each channel is in the same direction.

The preceding list is by no means exhaustive: in fact, the best receiver may result from a combination of some of the principles inherent in the above receivers. It is recommended that the problem of selecting a radiometer system suitable for scanning the range of 20 to 28 kmc be considered by competent engineers well-versed in microwave techniques and the state of the art.

Furthermore, it is entirely possible that the radiometer system developed for *K*-band will not prove feasible at 50 to 70 kmc or 100 to 150 kmc. Therefore, serious consideration should be given to the concurrent development of these systems.

V. SUMMARY

The various molecular resonances which may be important in planetary atmospheres have been reviewed so far as present data will allow. It can be seen, by examining Table 2 and the Appendices, that three frequency regions may be expected to include most of the molecules. The Report also outlines, very briefly, the scientific justifications for initiating the receiver development. It should be emphasized that considerable data can be obtained by terrestrial experiments alone and that this, in itself, is sufficient reason to begin the development. Finally, the characteristics of a sweep-frequency receiver suitable for the H_2O line are discussed and other approaches to the same problem are presented. The radiometer parameters presented here are to be considered only typical, and any final system should allow for many variable and uncertain factors. Thus, pilot models should include, if possible, provisions for different time constants, sweep ranges, sweep rates, and bandwidths.

APPENDIX A

Known NH_3 Frequencies and Intensities

The following is a list of the measured line frequencies of $N^{14}H_3$ and their quantum numbers and intensities. The intensities are calculated assuming $T = 300°K$ and $\Delta\nu = 26$ mc for 1 mm Hg. The number in parentheses is the exponent of 10. Thus 2.0 (−7) is 2.0×10^{-7}. (See Ref. 1 and 2.)

J	K	Frequency, mc	Intensity[a], cm^{-1}
11	4	11947.14	2.0 (−7)
10	1	12010.26	3.0 (−8)
12	6	12251.46	3.9 (−7)
10	2	12332.72	1.3 (−7)
11	5	12923.10	4.3 (−7)
14	9	12951.32	1.4 (−7)
13	8	13297.47	1.8 (−7)
10	3	13296.37	7.6 (−7)
9	1	(13612.36)	1.1 (−7)
		(13612.08)	
10	4	13700.96	8.1 (−7)
9	2	13974.54	4.9 (−7)
11	6	14224.74	1.8 (−6)
9	3	14376.56	2.5 (−6)
10	5	14822.70	1.7 (−6)
16	12	15193.54	4.9 (−8)
15	11	15195.98	6.6 (−8)
		(15233.12)	
8	1	(15233.36)	3.6 (−7)
14	10	15268.24	1.7 (−7)
13	9	15412.52	8.2 (−7)
9	4	15523.96	3.0 (−6)
12	8	15632.88	9.1 (−7)
8	2	15639.84	1.6 (−6)
11	7	15933.32	1.9 (−6)
10	6	16319.38	7.4 (−6)
8	3	16455.13	8.8 (−6)
9	5	16798.3	8.7 (−6)
7	1	16841.3	3.5 (−6)
7	2	17291.6	1.0 (−5)
8	4	17378.1	1.5 (−6)
7	3	18017.6	4.3 (−6)

J	K	Frequency, mc	Intensity[a], cm^{-1}
12	9	18127.2	4.7 (−6)
11	8	18162.6	4.8 (−6)
13	10	18178.0	1.1 (−6)
10	7	18285.6	9.4 (−6)
14	11	18313.9	4.5 (−7)
6	1	18391.6	4.2 (−6)
9	6	18499.5	3.4 (−5)
15	12	18535.1	3.6 (−7)
8	5	18808.7	2.8 (−5)
16	13	18842.9	6.6 (−8)
6	2	18884.9	2.6 (−5)
7	4	19218.52	4.0 (−5)
6	3	19757.56	1.1 (−4)
5	1	19838.4	1.8 (−5)
5	2	20371.48	5.6 (−5)
8	6	20719.20	1.0 (−4)
9	7	20735.46	3.3 (−5)
7	5	20804.80	7.4 (−5)
10	8	20852.51	1.9 (−5)
6	4	20994.62	9.9 (−5)
11	9	21070.73	2.0 (−5)
4	1	21134.37	4.0 (−5)
5	3	21285.30	2.3 (−4)
12	10	21391.55	5.2 (−6)
4	2	21703.34	1.1 (−4)
13	11	21818.1	6.0 (−7)
3	1	22234.51	6.9 (−5)
14	12	22355	2.2 (−6)
5	4	22653.00	2.2 (−4)
4	3	22688.24	4.4 (−4)
6	5	22732.45	1.7 (−4)

[a] In this column, numbers in parentheses are exponents of 10.

J	K	Frequency, mc	Intensity[a], cm^{-1}	J	K	Frequency, mc	Intensity[a], cm^{-1}
3	2	22834.10	2.0 (−4)	6	6	25056.04	6.9 (−4)
7	6	22924.91	2.9 (−4)	12	11	25695.23	1.3 (−5)
15	13	23004	4.8 (−7)	7	7	25715.14	2.7 (−4)
2	1	23098.78	1.1 (−4)	8	8	26518.91	2.0 (−4)
8	7	23232.20	9.9 (−5)	13	12	26655.00	1.3 (−5)
9	8	23657.46	6.5 (−5)	9	9	27478.00	2.8 (−4)
1	1	23694.48	1.9 (−4)	14	13	27772.52	3.0 (−6)
2	2	23722.61	3.2 (−4)	10	10	28604.73	9.0 (−5)
16	14	23777.4	1.9 (−7)	15	14	29061.14	1.4 (−6)
3	3	23870.11	7.9 (−4)	11	11	29914.66	5.5 (−5)
4	4	24139.39	4.3 (−4)	12	12	31424.97	6.2 (−5)
10	9	24205.25	7.8 (−5)	13	13	33156.95	1.7 (−5)
5	5	24532.94	4.0 (−4)	14	14	35134.44	8.7 (−6)
17	15	24680.1	1.1 (−7)	15	15	37385.18	8.3 (−6)
11	10	24881.90	2.2 (−5)	16	16	39941.54	1.9 (−6)

[a]In this column, numbers in parentheses are exponents of 10.

APPENDIX B

Frequencies of Measured Lines of Molecules

The following is a list of frequencies of the measured lines of molecules expected to be of importance in the terrestrial or planetary atmospheres. Line strengths and quantum-number assignments are not available in all cases and have been omitted for sake of brevity. Lines whose frequencies are less than 10,000 mc are omitted. Where a frequency range is shown, many lines, all accurately measured, are known to lie within this range.

Molecule	Frequency, mc
CO	115,271.195
	230,537.974
	345,795.900
N_2O	–
	25,123.25
	50,246.03
	100,491.76
	125,613.68
O_2	–
	53,066
	53,592
	54,130
	54,673
	55,221
	55,784
	56,265
	56,363
	56,969
	57,612

Molecule	Frequency, mc
O_2	58,324
	58,446
	59,163
	59,592
	60,306
	60,435
	61,152
	61,800
	62,412
	62,486
	62,998
	63,568
	64,128
	64,679
	65,223
	65,762
	66,296
	66,828
	118,746

Molecule	Frequency, mc
H_2O	22,235.22
	185,000
NO_2	15,290 ± 360
	16,020 ± 12
	26,629 ± 66
	39,148 ± 95
	40,822 ± 160
NO	150,210 ± 35
	150,510 ± 135
	250,460 ± 23
	250,760 ± 55
	257,850 ± 30
OH	13,434.62
	13,441.36
	23,806.5
	23,818.18
	23,826.90
	23,837.8
	36,983.47
	36,994.43

Molecule	Frequency, mc
O_3 *	10,226
	11,073
	14,866
	16,163
	23,860
	25,300
	25,511
	25,649
	27,862
	28,960
	30,052
	30,181
	30,525
	36,023
	37,832
	42,833
	43,654
	96,229
	101,737
	118,364

*In the range from 10,000 to 300,000 mc there are 106 lines whose frequencies have been calculated but which have not yet been observed in the laboratory. Observed lines are given above (See Ref. 3).

Molecule	Frequency, mc
SO_2	20,335.4
	20,460.1
	22,220.3
	22,482.5
	22,733.8
	22,904.9
	22,928.5
	23,034.8
	23,414.3
	23,733.0
	24,039.5

Molecule	Frequency, mc
SO_2	24,083.4
	24,319.7
	25,049.1
	25,171.0
	25,392.8
	26,777.2
	28,858.1
	29,321.3
	53,529.2
	59,225.0
	69,576.1

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